Model Questions with Answers (Long)

Module -1

1. Explain different modes of heat transfer?

Ans: - There are three modes of heat transfer

(i) Conduction
(ii) Convection
(iii) Radiation

Conduction

- It is a mechanism of heat propagation from a region of higher temperature to a region of lower temperature within a medium or between different mediums in direct physical contact.
- It does not involve any macroscopic movement of matters relative to one another.
- It is mainly due to random molecular motion and so it is called microform of heat transfer or diffusion of energy.
- Thermal energy may be transferred by means of electrons which are free to move through the lattice structure of the material.
- It may also transfer as vibrational energy in the lattice structure.
- It is a microscopic form of heat transfer.

Convection

Convection is the mode of heat transfer between a surface and a fluid moving over it.

- The energy transfer in convection is mainly due to bulk motion of fluid particles.
- If this motion is mainly due to density variations then it is called free or natural convection.
- If this motion is produced by some superimposed velocity field then it is called forced convection.

Radiation

- It is the transmission of heat in the form of radiant energy or wave motion from one body to another across an intervening space.
- An intervening medium is not even necessary and the radiation can be affected through vacuum also and more effective is in vacuum only.
- Mechanism of radiation is divided into 3phases
  - Conversion of thermal energy of the hot source into electromagnetic waves.
  - Passage of wave motion through intervening medium.
  - Transformation of waves into heat.
  - Thermal radiation is limited to wavelengths ranging from 0.01 to 100μm of the electromagnetic spectrum.

Examples: Boiler furnace, solar radiation, earth radiation, due to high temperature surfaces.

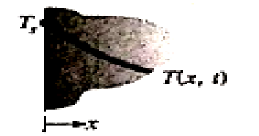
2. Explain 1st kind ,2nd kind and 3rd kind boundary condition with proper diagram.

Ans:-

TABLE Boundary conditions for the heat diffusion equation at the surface ($x = 0$)

1. Constant surface temperature

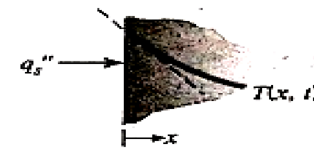
$$T(0, t) = T_s$$



2. Constant surface heat flux

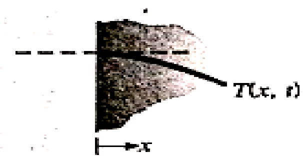
(a) Finite heat flux

$$-k\frac{\partial T}{\partial x}\Big|_{x=0} = q_s''$$



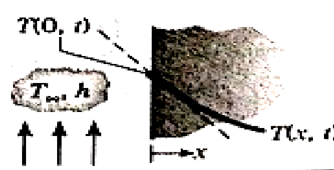
(b) Adiabatic or insulated surface

$$\frac{\partial T}{\partial x}\Big|_{x=0} = 0$$



3. Convection surface condition

$$-k\frac{\partial T}{\partial x}\Big|_{x=0} = h[T_\infty - T(0, t)]$$



3. Explain the laws governing conduction, convection and radiation?

Ans:- **<u>Fourier's laws of heat conduction</u>**

"The rate of flow of heat through a solid is directly proportional to the area of the section at right angles to the direction of heat flow, and to change of temperature with respect to the length of the path of the heat flow."

Mathematically, it can be written as

$$Q \; \alpha \; Adt/dx$$

Where, Q= Heat flow through a body per unit time (in watts) W,

A = Surface area of heat flow (perpendicular to the direction of flow),m2

dt = Temperature difference of the faces of the solid of thickness 'dx' through which heat flows, ^oC or K,

dx = Thickness of body in the direction of flow, m.

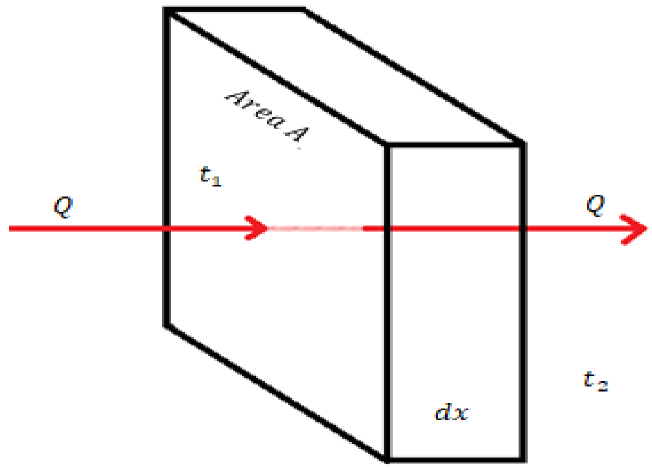
Thus,

$$Q=-KAdt/dx$$

Where, K = Constant of proportionality and is known as thermal conductivity of the body.

The –ve sign is to take care of the decreasing temperature along with the direction of increasing thickness or the direction of heat flow.

The temperature gradient dt/dx is always negative along positive x direction and, therefore , the value as Q becomes + ve.



Newton's law of cooling

The rate equation for the convective heat transfer between a surface and an adjacent fluid is given by Newton's law of cooling.

$$Q=hA(t_s-t_f)$$

Where Q= rate of heat transfer,
A= area exposed to heat transfer,
t_s = surface temperature
t_f = fluid temperature, and
h=co-efficient of convective heat transfer
The units of h are,
$h=Q/A(t_s-t_f)$ =W/m^2°C OR W/m^{2}K
The coefficient of convective heat transfer 'h' is defined as
"the amount of heat transferred for a unit temperature difference between the fluid and unit area of surface in unit time."
The term 1/hA is called convective thermal resistance.

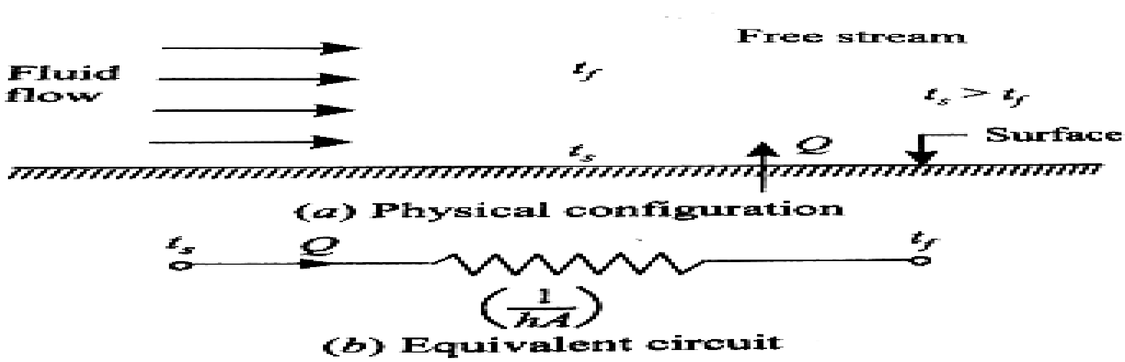


Fig. Convective heat-transfer

Stefan-Boltzmann law

The law states that the emissive power of a black body is directly proportional to fourth power of its absolute temperature.
i.e. $Q \propto T^4$
or $Q = \sigma A T^4$
where σ = Stefan-Boltzmann constant= $5.67 \times 10^{-8} W/m^2K^4$.

4. Consider steady 1D heat flow in a plate of 20 mm thickness with uniform heat generation 80 MW/m3 .The left face and right faces are kept at a constant temperature 160⁰C and 120⁰C respectively. The plate has constant thermal conductivity of 200W/m-K . Find a) The location of maximum temperature within the plate from its left side b) The maximum temperature within the plate.

Ans :-

Answer:- $\frac{d^2T}{dx^2} + \frac{q_g'''}{K} = 0.$

$\Rightarrow \frac{d^2T}{dx^2} = -\frac{q_g'''}{K}$

Upon integration, we get:-

$\Rightarrow \frac{dT}{dx} = -\frac{q_g''' x}{K} + C_1$

Integrating again we get:-

$\Rightarrow T = -\frac{q_g''' x^2}{2K} + C_1 x + C_2.$

At $x = 0$, $T = 160°C$

At $x = L = 20 \times 10^{-3}$ m, $T = 120°C$.

$\Rightarrow 160 = 0 + 0 + C_2 \Rightarrow \boxed{C_2 = 160}$

$120 = -\frac{80 \times 10^6 \times (20 \times 10^{-3})^2}{2 \times 200} + C_1 \times (20 \times 10^{-3}) + 160.$

$\Rightarrow -40 = -\frac{80 \times \cancel{10^6} \times \cancel{400} \times \cancel{10^{-6}}}{\cancel{400}} + C_1 \times (0.02).$

$\Rightarrow -40 = -80 + C_1 \times (0.02) \Rightarrow 40 = C_1 \times 0.02 \Rightarrow C_1 = \frac{40}{0.02} = 2000.$

For maximum temperature, $\frac{dT}{dx} = 0.$

$\Rightarrow 0 = -\frac{80 \times 10^6 \times x}{200} + 2000.$

$\Rightarrow +\frac{80 \times 10^6 \times x}{200} = 2000 \Rightarrow x = \frac{400000}{80 \times 10^6} = \frac{0.5}{100}$ m.

$= 0.005$ m $= 0.005 \times 1000$ mm $= 5$ mm.

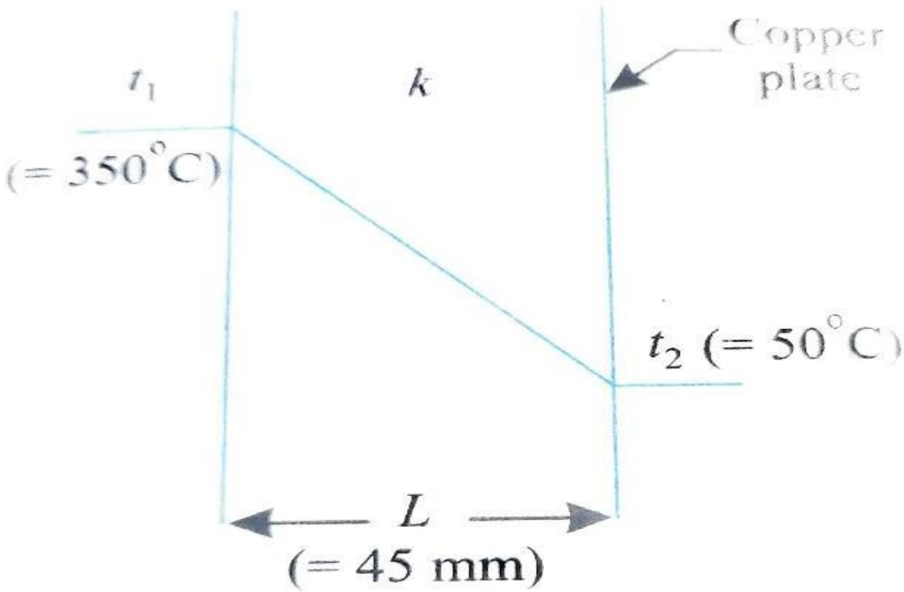
$x = 5$ mm

$T = -\frac{80 \times 10^6 \times (5 \times 10^{-3})^2}{2 \times 200} + 2000 \times (5 \times 10^{-3}) + 160.$

$= 160 + 10 - \frac{400 \times 5}{400} = 160 + 10 - 5 = 165°C.$

5. Calculate the rate of heat transfer per unit area through a copper plate 45 mm thick , whose one face maintained at 350^0C and the other face at 50^0C.Take thermal conductivity of copper as 370W/m^{0}C.

Ans:-



Temperature difference, dt=t2-t1=50-350

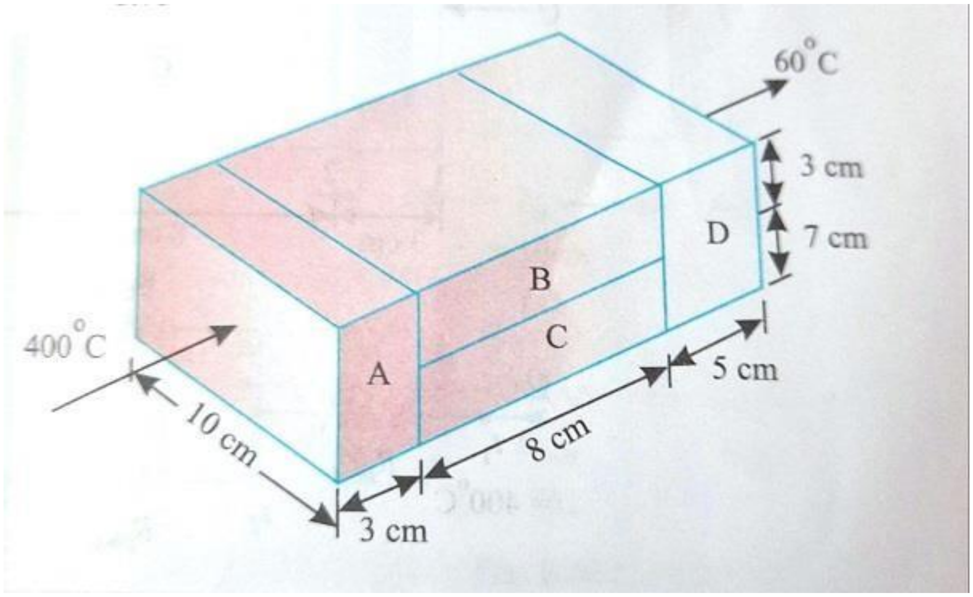
Thickness of copper plate, L= 45mm =0.045m Thermal conductivity of copper ,k =370W/m^{0}C

Rate of heat transfer per unit area , q:

From Fourier's law:- Q=-KAdt/dx=-KA(t2-t1)/L

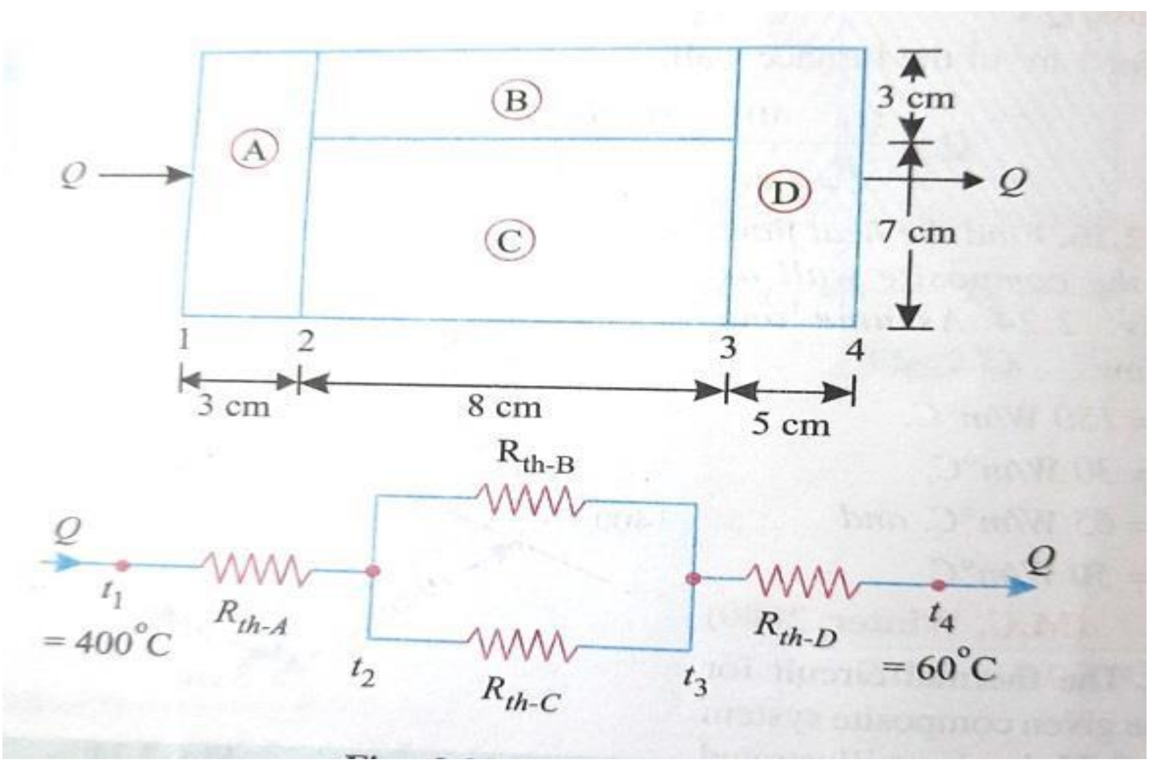
or $q=Q/A=-370\times(50-350)/0.045=2.466\times10^6 W/m^2$.

6. Find the heat flow rate through the composite wall as shown in the figure. Assume one dimensional flow.



K_A =150 W/m⁰C
K_B =30 W/m⁰C
K_C=65 W/m⁰C
K_D =50 W/m⁰C

The thermal circuit for the above problem is given as below:-



Thickness:

L_A =3 cm=0.03 m, L_B = L_C =8 cm =0.08 m, L_D =5 cm= 0.05 m

Areas:

A_A =0.1 X 0.1= 0.01 m^2, A_B =0.1 X 0.03 =0.003 m^2

A_C =0.1 X 0.07 =0.007 m^2, A_D =0.1 X 0.1 =0.01 m^2

Heat flow rate, Q:

The thermal resistances are given by,

$R_{th\text{-}A}$ = 0.03/(150×0.01)=0.02

$R_{th\text{-}B}$= 0.08/(30×0.003)=0.89

$R_{th\text{-}C}$ = 0.08/(65×0.007)=0.176

$R_{th\text{-}D}$ = 0.05/(50×0.01)=0.1

The equivalent thermal resistance for the parallel thermal resistance $R_{th\text{-}B}$ and $R_{th\text{-}C}$ is given by

$$\frac{1}{(R_{th})_{eq}} = \frac{1}{R_{th-B}} + \frac{1}{R_{th-C}} = \frac{1}{0.89} + \frac{1}{0.176} = 6.805$$

$$(R_{th})_{total} = R_{th-A} + (R_{th})_{eq} + R_{th-D} = 0.02 + 0.147 + 0.1 = 0.267$$

Hence,

$Q = (\Delta t)_{overall}/(R_{th})_{ovearall}$ = (400-60)/0.267=1273.4 W

Module -2

7. Show by dimensional analysis for free convection Nu =ϕ(Pr,Gr)

Ans :-

Ans:- The heat transfer coefficient 'h' may be expressed as follows:-

$$h = f(\rho, L, \mu, C_p, K, \beta g \Delta t)$$

$$= f_1(\rho, L, \mu, K, h, C_p, \beta g \Delta t)$$

Total no of variables $= n = 7$.

Fundamental dimensions in the problem $= 4\ (M, L, T, \theta)$

Number of dimensionless π-terms $= (n-m) = (7-4) = 3$.

$$f_1(\pi_1, \pi_2, \pi_3) = 3.$$

We choose ρ, L, μ and K as the core group (repeating variables) with unknown exponents. The groups to be formed are now represented as the following π groups:

$$\pi_1 = \rho^{a_1} L^{b_1} \mu^{c_1} K^{d_1} h.$$

$$\pi_2 = \rho^{a_2} L^{b_2} \mu^{c_2} K^{d_2} . C_p$$

$$\pi_3 = \rho^{a_3} L^{b_3} . \mu^{c_3} K^{d_3} . \beta g \Delta t$$

π_1-term:-

$$M^0 L^0 T^0 \theta^0 = [ML^{-3}]^{a_1} [L]^{b_1} [ML^{-1}T^{-1}]^{c_1} [MLT^{-3}\theta^{-1}]^{d_1} [MT^{-3}\theta^{-1}].$$

Equating the exponents of M, L, T and θ respectively, we get:-

$a_1 + c_1 + d_1 + 1 = 0.$

$-3a_1 + b_1 - c_1 + d_1 = 0.$ $\Rightarrow a_1 = 0,\ b_1 = 1,\ c_1 = 0,\ d_1 = -1$

$-c_1 - 3d_1 - 3 = 0.$

$-d_1 - 1 = 0.$ $\therefore \pi_1 = LK^{-1}h$ or $\pi_1 = \frac{hL}{K}.$

π_2-term:- $M^0 L^0 T^0 \theta^0 = [ML^{-3}]^{a_2} [L]^{b_2} [ML^{-1}T^{-1}]^{c_2} [MLT^{-3}\theta^{-1}]^{d_2} [L^2 T^{-2} \theta^{-1}]$

$a_2 + c_2 + d_2 = 0.$

$-3a_2 + b_2 - c_2 + d_2 + 2 = 0$ $\Rightarrow a_2 = 0,\ b_2 = 0,\ c_2 = 1,$ $d_2 = -1.$

$-c_2 - 3d_2 - 2 = 0.$

$-d_2 - 1 = 0.$ $\therefore \pi_2 = \mu K^{-1} C_p$ or $\pi_2 = \frac{\mu C_p}{K}.$

π_3 term:-

$$M^0L^0T^0\theta^0 = [ML^{-3}]^{a_3}[L]^{b_3}[ML^{-1}T^{-1}]^{c_3}[MLT^{-3}\theta^{-1}]^{d_3}$$

$$[LT^{-2}]$$

Equating the exponents of M, L, T, θ respectively we get:-

$$a_3 + c_3 + d_3 = 0.$$

$$-3a_3 + b_3 - c_3 + d_3 + 1 = 0 \Rightarrow a_3 = 2,\ b_3 = 3,\ c_3 = -2,\ d_3 = 0.$$

$$-c_3 - 3d_3 - 2 = 0 \qquad \therefore \pi_3 = \frac{(\beta g \Delta t)\rho^2 L^3}{\mu^2}$$

$$-d_3 = 0.$$

$$= \frac{(\beta g \Delta t) L^3}{\nu^2}.$$

$$\therefore Nu = \phi(Pr)(Gr)$$

$$\text{i.e. } Nu = C(Pr)^n (Gr)^m$$ where Gr = Grashoff number

Here C, n and m are constants and may be evaluated experimentally.

8. A plate of length 750 mm and width 250 mm has been placed longitudinally in a stream of crude oil which flows with a velocity of 5 m/sec. If the oil has a specific gravity of 0.8 and kinematic viscosity of 1 stoke ,calculate :

(i) Boundary layer thickness at the middle of plate ,

(ii) Shear Stress at the middle of plate,

iii) Friction drag on one side of the plate

Ans :-

Ans:- Width of the plate, $B = 250mm = 0.25m$.

Velocity of oil, $U = 5 m/sec$.

Specific gravity of oil = 0.8

Kinematic viscosity of oil = 1 stoke = $1 \times 10^{-4} m^2/sec$.

(i) boundary layer thickness at middle of the plate δ:

$$R_e = \frac{\rho U x}{\mu} = \frac{Ux}{\nu} = \frac{5 \times 0.375}{1 \times 10^{-4}} = 18750.$$

Since $Re_x < 5 \times 10^5$, therefore boundary layer is of laminar type and Blasius solution gives

$$\delta = \frac{5x}{(R_{ex})^{1/2}} = \frac{5 \times 0.375}{18{,}750} = 0.01369 m = 13.69 mm.$$

(ii) Shear Stress at the middle of plate, τ_0:

$$C_{fx} = \frac{0.664}{(Re_x)^{1/2}} = \frac{0.664}{\sqrt{18750}} = 4.89\times10^{-3}.$$

$$C_{fx} = \frac{\tau_0}{\frac{1}{2}\rho U^2}$$

$$\Rightarrow \tau_0 = C_{fx}\times\frac{1}{2}\rho U^2$$

$$= 4.89\times10^{-3}\times\frac{1}{2}\times(0.8\times1000)\times5^2$$

$$= 48.49\ N/m^2 \text{ (Ans)}$$

(iii) Friction drag on one side of the plate, F_D:

$$Re_L = \frac{UL}{\nu} = \frac{5\times0.75}{1\times10^{-4}} = 37,500 \text{ (laminar)} < 5\times10^5$$

$$\bar{C_f} = \frac{1.328}{\sqrt{Re_L}} = \frac{1.328}{\sqrt{37500}} = 6.858\times10^{-3}$$

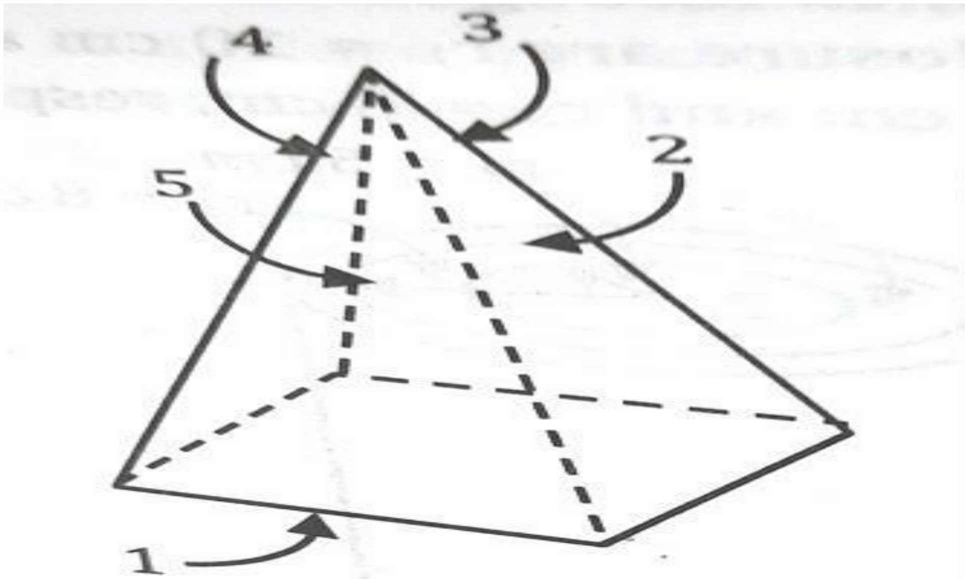
$\therefore$ Friction Drag $= F_D = \bar{C_f}\times\frac{1}{2}\times\rho U^2\times$ Area of plate on one side

$$= 6.858\times10^{-3}\times\frac{1}{2}\times(0.8\times1000)\times5^2\times0.75\times0.25.$$

$$= 12.86N.$$

Module -3

9. Determine the view factors from the base of the pyramid shown in the figure to each of its four side surfaces.The base of the pyramid is a square and its side surfaces are isosceles triangles.



The Pyramid

Ans :-

The base of the pyramid (surface 1) and its four side surfaces (surfaces 2, 3 , 4 and 5) form a five surface enclosure.The four side surfaces are symmetric about the base surface.

Then, by symmetry rule, we have $F_{12}=F_{13}=F_{14}=F_{15}$

Also, by summation rule

$F_{11}+F_{12}+F_{13}+F_{14}+F_{15}=1$

But $F_{11}=0$, since base is a flat surface.

Hence $F_{12}=F_{13}=F_{14}=F_{15}=0.25$

10. Calculate the following for an industrial furnace in the form of a black body and emitting radiation at 2500 ^oC :

(i) Monochromatic emissive power at 1.2 μm length

(ii) Wavelength at which the emission is maximum

(iii)Maximum emissive power

(iv) Total emmisive power and

(v) Total emissive power of the furnace if it is assumed as a real surface with emissivity equal to 0.9

Ans:-

Ans:-

(i) According to Planck's law,

$$(E_\lambda)_b = \frac{C_1 \lambda^{-5}}{\exp\left(\frac{C_2}{\lambda T}\right) - 1}$$

where $C_1 = 3.742 \times 10^{8} \, W\mu m^4/m^2 = 0.3742 \times 10^{-15} \, Wm^4/m^2$

$C_2 = 1.4388 \times 10^{-2}$ mK.

$$(E_\lambda)_b = \frac{0.3742\times10^{-15} \times (1.2 \times 10^{-6})^{5}}{\exp\left(\frac{1.4388\times10^{-2}}{1.2\times10^{-6}\times 2773}\right)-1} = 2.014\times10^{12} \, W/m^2$$

(ii) $\lambda_{max} = \frac{2898}{T} = \frac{2898}{2773} = 1.045 \mu m.$

(iii) $(E_{\lambda b})_{max}$ = Maximum Emissive Power

$= 1.285 \times 10^{-5} T^5$

$= 1.285 \times 10^{-5} \times (2773)^5 = 2.1 \times 10^{12} W/m^2$ per metre length.

(iv) Total emissive power, E_b:

$E_b = \sigma T^4 = 5.67 \times 10^{-8} \times (2773)^4 = 5.67 \times \left(\frac{2773}{100}\right)^4$

$= 3.352 \times 10^6 W/m^2.$ (Ans).

(v) Total emissive power, E with emissivity $(\varepsilon) = 0.9$

$E = \varepsilon \sigma T^4 = 0.9 \times 5.67 \times \left(\frac{2773}{100}\right)^4 = 3.017 \times 10^6 W/m^2.$

MODULE 4

11. A counter –flow heat exchanger, through which passes 12.5 kg/s of air to be cooled from 540 °C to 146 °C, contains 4200 tubes, each having a diameter of 30 mm. The inlet and outlet temperatures of cooling water are 25 °C and 75 °C respectively. If the water side resistance to flow is negligible, calculate the tube length required for this duty.

For turbulent flow inside tubes: Nu =0.023 $Re^{0.8}Pr^{0.4}$

Properties of the air at the average temperature are as follows:-

ρ=1.009 kg/m^3,C_p=1.0082 KJ/Kg °C,μ=2.075×10^{-5} kg/ms(Ns/m^2) and K=3.003×10^{-2} W/m°C

Ans:-

Ans:- Given,

$\dot{m}_h = 12.5$ kg/sec, $t_{h_1} = 540°C$, $t_{h_2} = 146°C$, $t_{c_2} = 75°C$,

$t_{c_1} = 25°C$, $N = 4200$, $d = 0.03$ m.

Reynolds number, $Re = \frac{\rho V D}{\mu}$

Mass flow $m = NAV\rho$

$$\rho V = \frac{m}{NA}$$

$$Re = \frac{md}{NA\mu} = \frac{12.5 \times 0.03}{4200 \times \pi/4 \times (0.03)^2 \times 2.075 \times 10^{-5}} = 6087.4$$

Prandtl number, $Pr = \frac{\mu C_p}{K} = \frac{2.075 \times 10^{-5} \times 1.0082 \times 10^3}{3.003 \times 10^{-2}} = 0.6966$

Nusselt number for turbulent flow

$$Nu = \frac{hd}{K} = 0.023 \times Re^{0.8} Pr^{0.4}$$

$$= 0.023 \times (6087.4)^{0.8} \times (0.6966)^{0.4}$$

$$= 21.2.$$

$$h = \frac{K}{d} \times 21.2 = \frac{3.003 \times 10^{-2}}{0.03} \times 21.2 = 21.22 \text{ W/m}^2{}°C.$$

Since the water side resistance to flow is negligible

$$\frac{1}{U} = \frac{1}{h} = \frac{1}{21.22} \text{ or } U = 21.22 \text{ W/m}^2{}°C.$$

$$\theta_m = \frac{\theta_1 - \theta_2}{\ln\left(\frac{\theta_1}{\theta_2}\right)} = \frac{(t_{h_1} - t_{c_2}) - (t_{h_2} - t_{c_1})}{\ln\left(\frac{t_{h_1} - t_{c_2}}{t_{h_2} - t_{c_1}}\right)}$$

$$= \frac{(540 - 75) - (146 - 25)}{\ln\left(\frac{540 - 75}{146 - 25}\right)} = 255.5°C$$

$$Q = \dot{m}_h C_{ph} \times (t_{h_2} - t_{h_1}) = UA\theta_m = U \times N \times \pi d \times L \times \theta_m.$$

$$\Rightarrow L = \frac{\dot{m}_h C_{ph} \times (t_{h_2} - t_{h_1})}{U \times N \times \pi d \times \theta_m} = \frac{12.5 \times (1.0082 \times 10^3) \times (540 - 146)}{21.22 \times 4200 \times \pi \times 0.03 \times 255.5}$$

$$= 2.31 \text{ m.}$$

ALL THE BEST